Single-Spin Asymmetry in Polarized p+A Collisions

Yuri Kovchegov
The Ohio State University

based on arXiv:1201.5890 [hep-ph] and more recent work with Matthew Sievert

(special thanks to Michael Lisa)

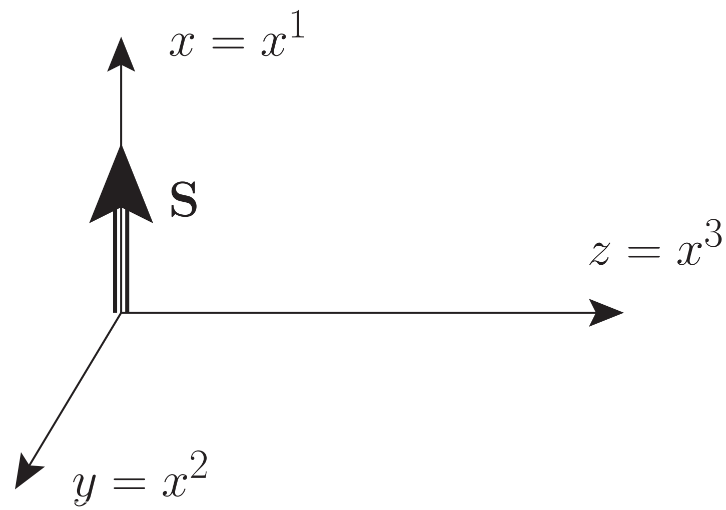
Outline

- Introduction (STSAs, saturation/CGC)
- Calculation of STSA in CGC
  - New mechanism: odderon exchange with the unpolarized nucleus
  - Sivers effect: including it into the CGC framework
- Conclusions and outlook

Introduction

Single Transverse Spin Asymmetry

- Consider polarized proton scattering on an unpolarized proton or nucleus.

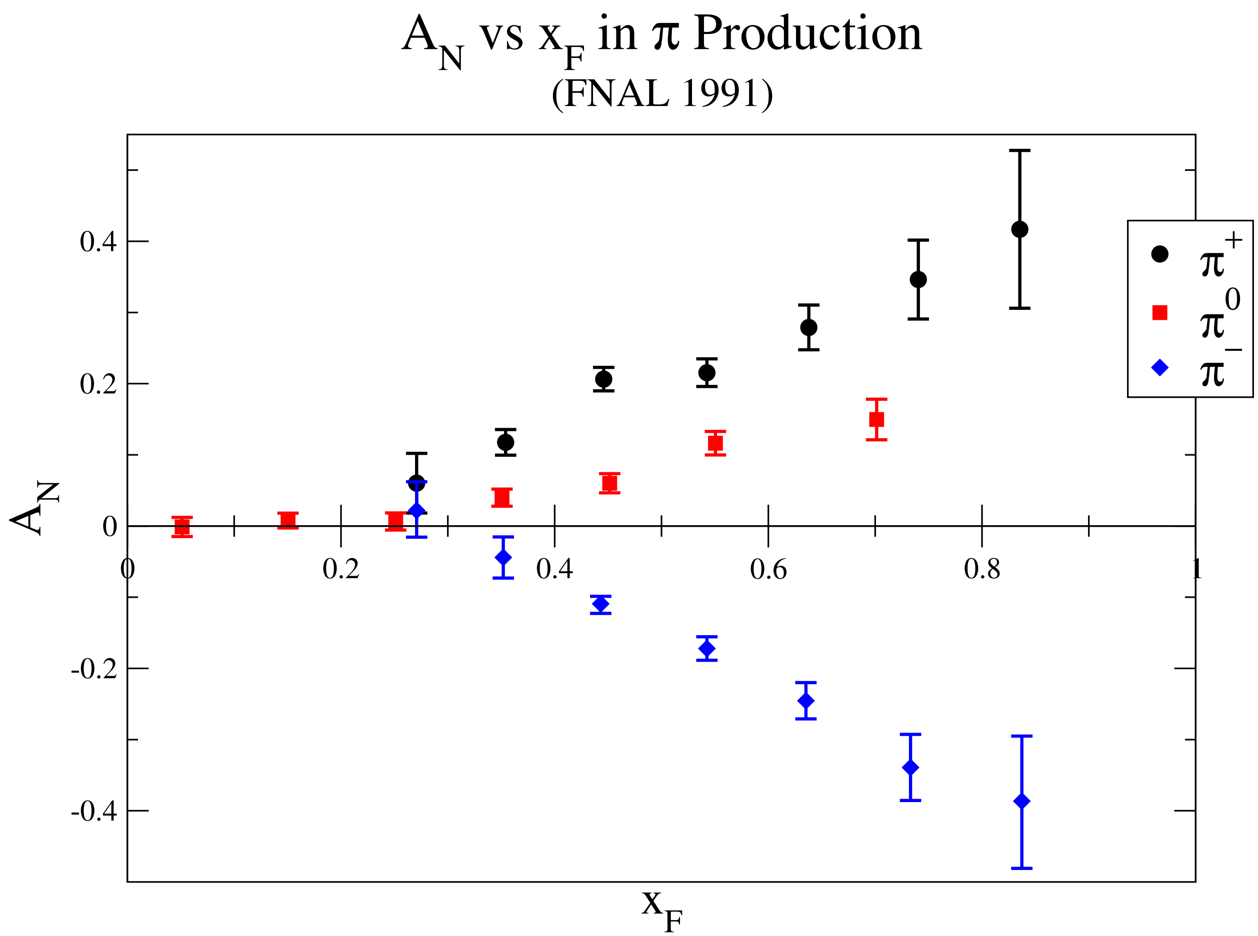


- Single Transverse Spin Asymmetry (STSA) is defined by

$$A_N(\mathbf{k}) \equiv \frac{\frac{d\sigma^\uparrow}{d^2k\,dy} - \frac{d\sigma^\downarrow}{d^2k\,dy}}{\frac{d\sigma^\uparrow}{d^2k\,dy} + \frac{d\sigma^\downarrow}{d^2k\,dy}} = \frac{\frac{d\sigma^\uparrow}{d^2k\,dy}(\mathbf{k}) - \frac{\mathbf{d}\sigma^\uparrow}{\mathbf{d^2k\,dy}}(-\mathbf{k})}{\frac{d\sigma^\uparrow}{d^2k\,dy}(\mathbf{k}) + \frac{\mathbf{d}\sigma^\uparrow}{\mathbf{d^2k\,dy}}(-\mathbf{k})} \equiv \frac{d(\Delta\sigma)}{2\,d\sigma_{unp}}$$

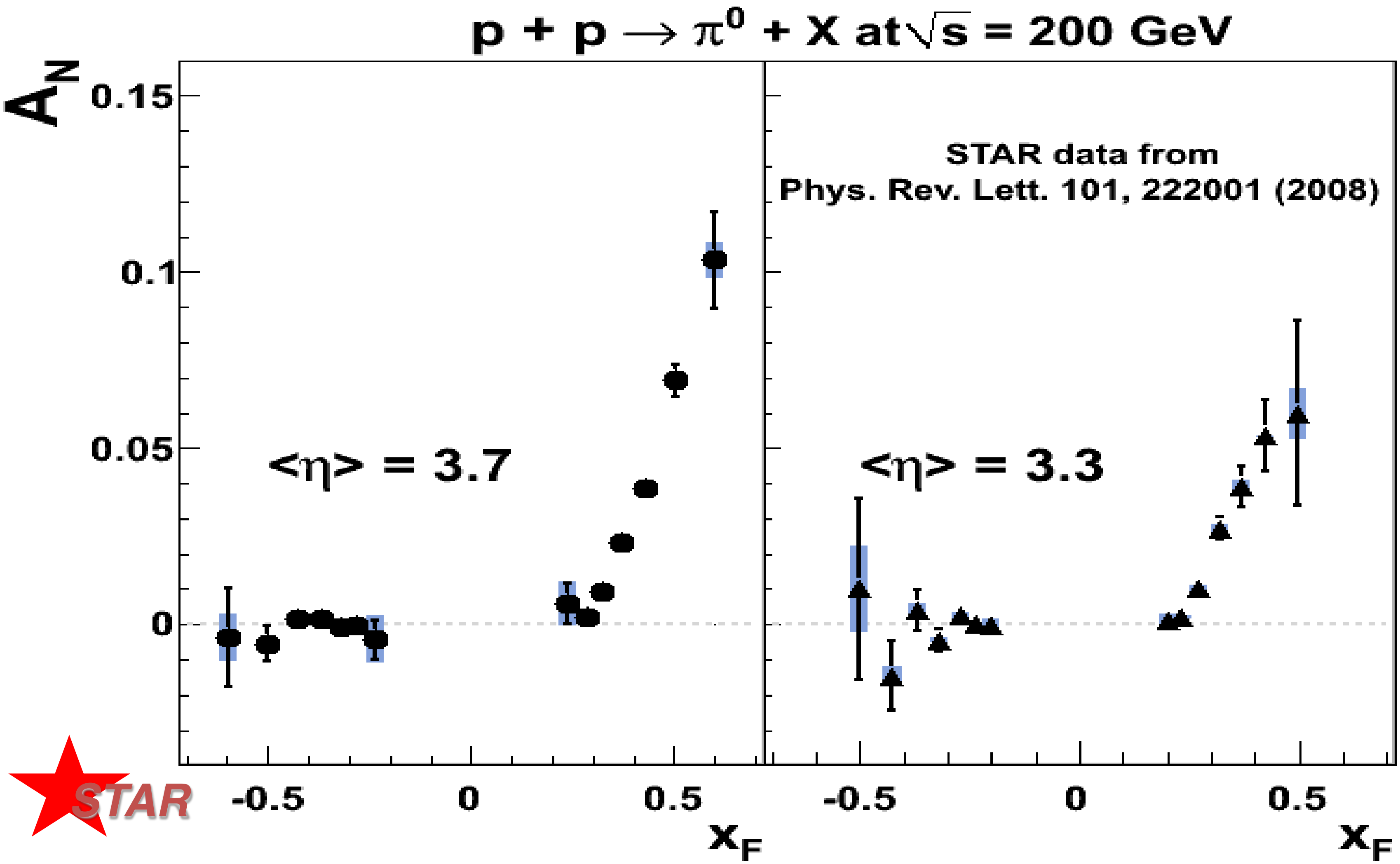
STSA: the data

- The asymmetry is non-zero, and is an increasing function of Feynman-x of the polarized proton:



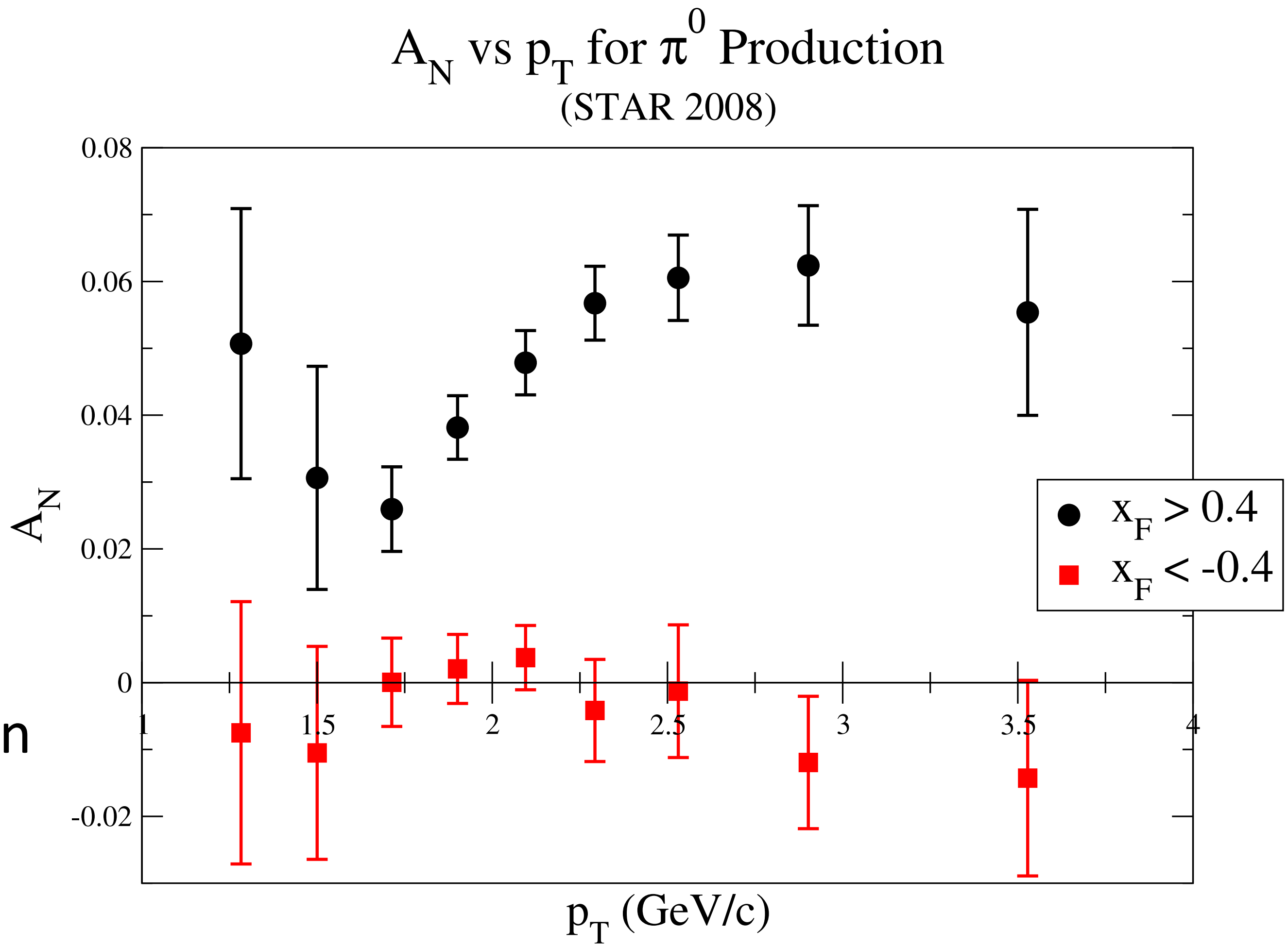
Fermilab E581 & E704 collaborations 1991

STSA: a more recent data



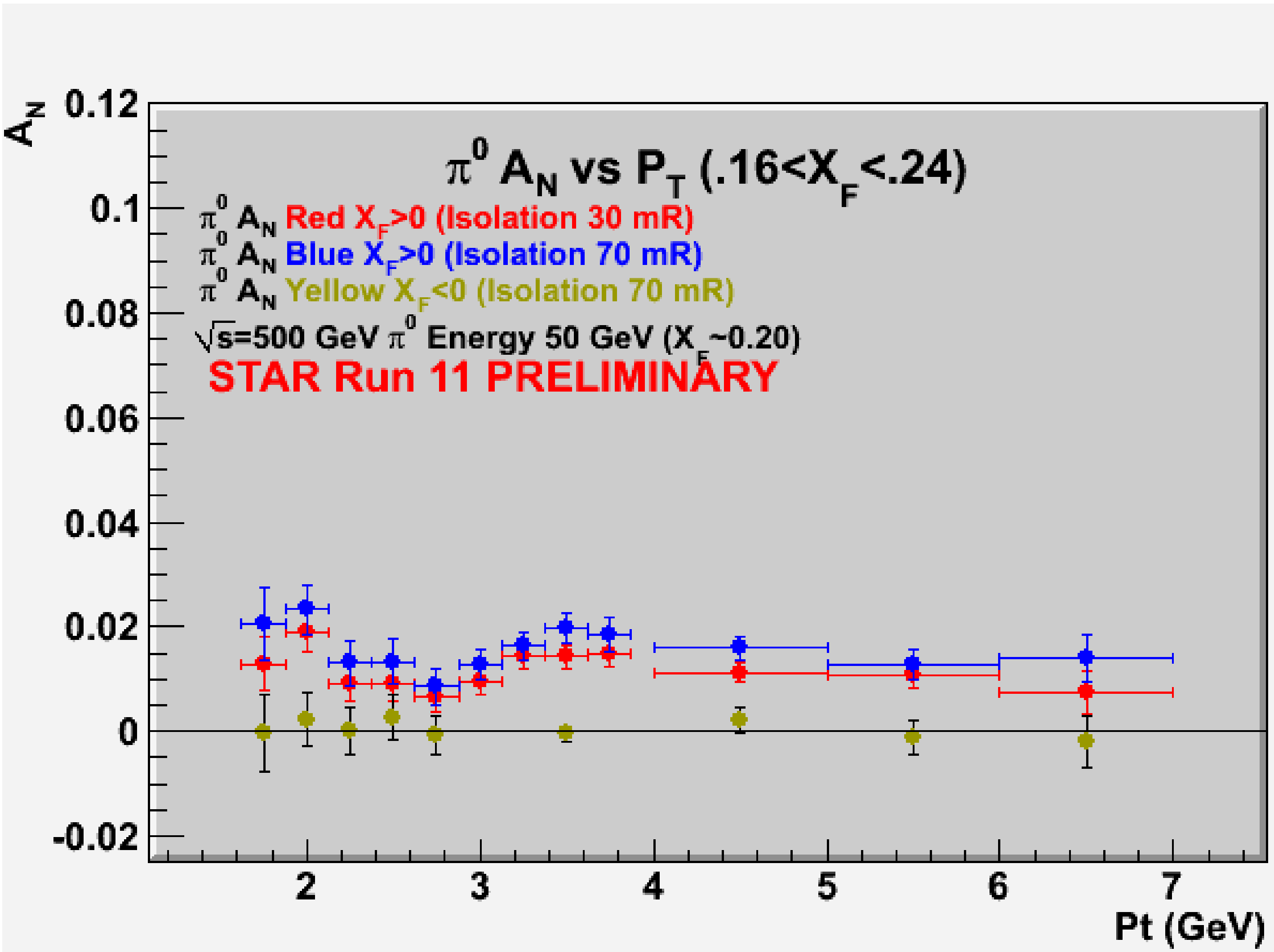
STSA: the data

- STSA is also a non-monotonic function of transverse momentum p_T, which has zeroes (nodes), where its sign changes:



RHIC,
STAR collaboration
2008

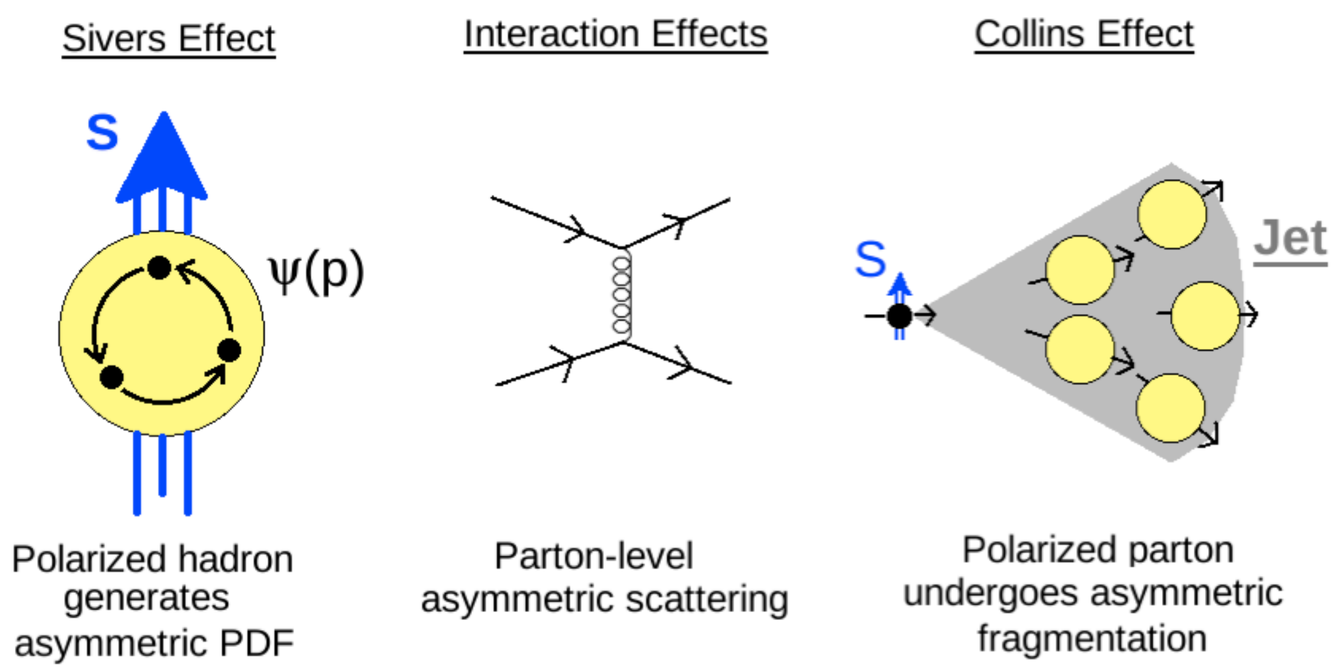
STSA: a more recent data



Theoretical Explanations

The origin of STSA (in the collinear/TMD factorization framework) is in

- polarized PDF (Sivers effect)
- polarized fragmentation (Collins effect)
- hard scattering



Need to understand STSAs in the saturation/CGC framework

- At RHIC, even in p↑+p collisions reach small values of x in the unpolarized proton → saturation effects may be present
- For p↑+A scattering, nuclear target would further enhance saturtion/CGC effects, making understanding the role of saturation in STSA a priority
- Spin-dependent probes may provide new independent tests of saturation/CGC physics.

High Energy QCD: saturation physics

- Saturation physics is based on the existence of a large internal momentum scale Q_S which grows with both energy s and nuclear atomic number A

$$\boxed{Q_S^2 \sim A^{1/3}\ s^{\lambda}}$$

such that

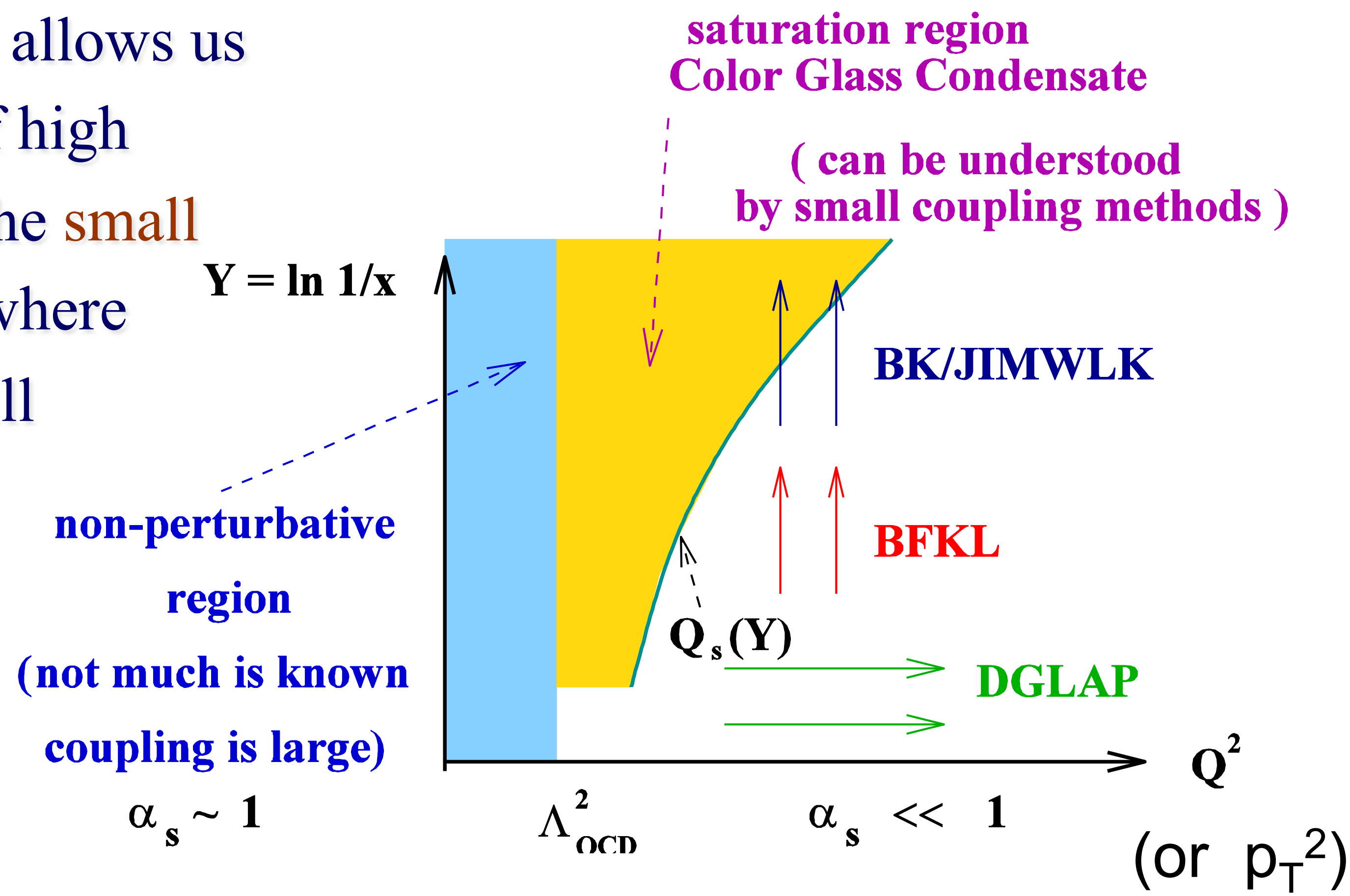
$$\boxed{\alpha_S = \alpha_S\left(Q_S\right) << 1}$$

and we can calculate total cross sections, particle spectra and multiplicities, etc, from <u>first principles</u>.

- Bottom line: everything is considered perturbative.

Map of High Energy QCD

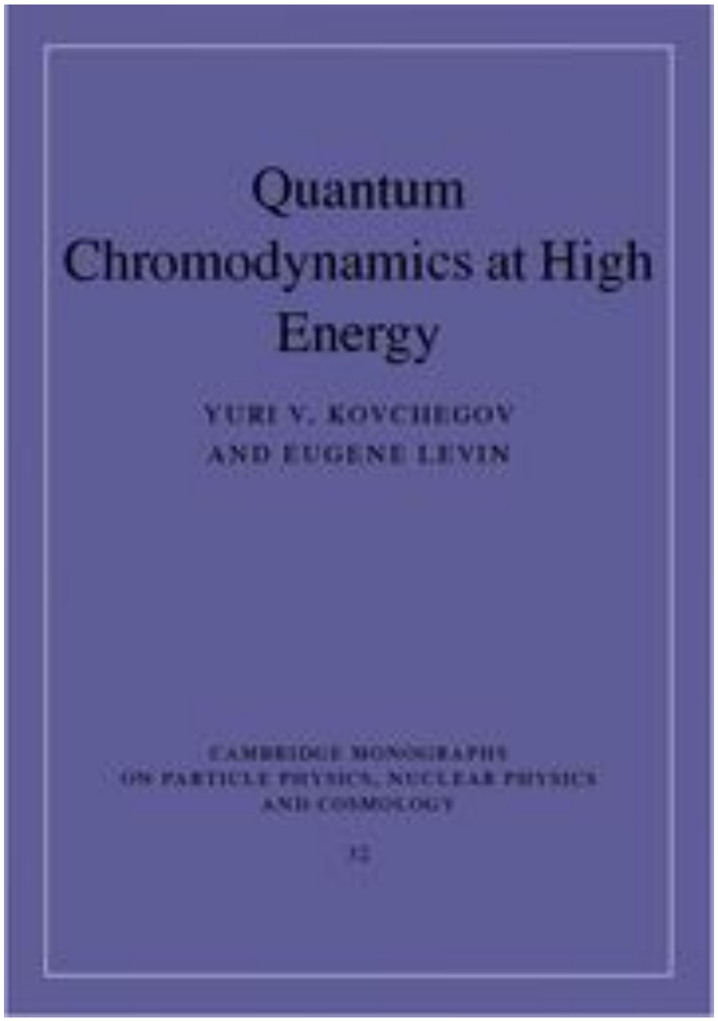
Saturation physics allows us to study regions of high parton density in the small coupling regime, where calculations are still under control!



Transition to saturation region is characterized by the saturation scale

$$Q_S^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

A reference



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Calculation of STSA in CGC

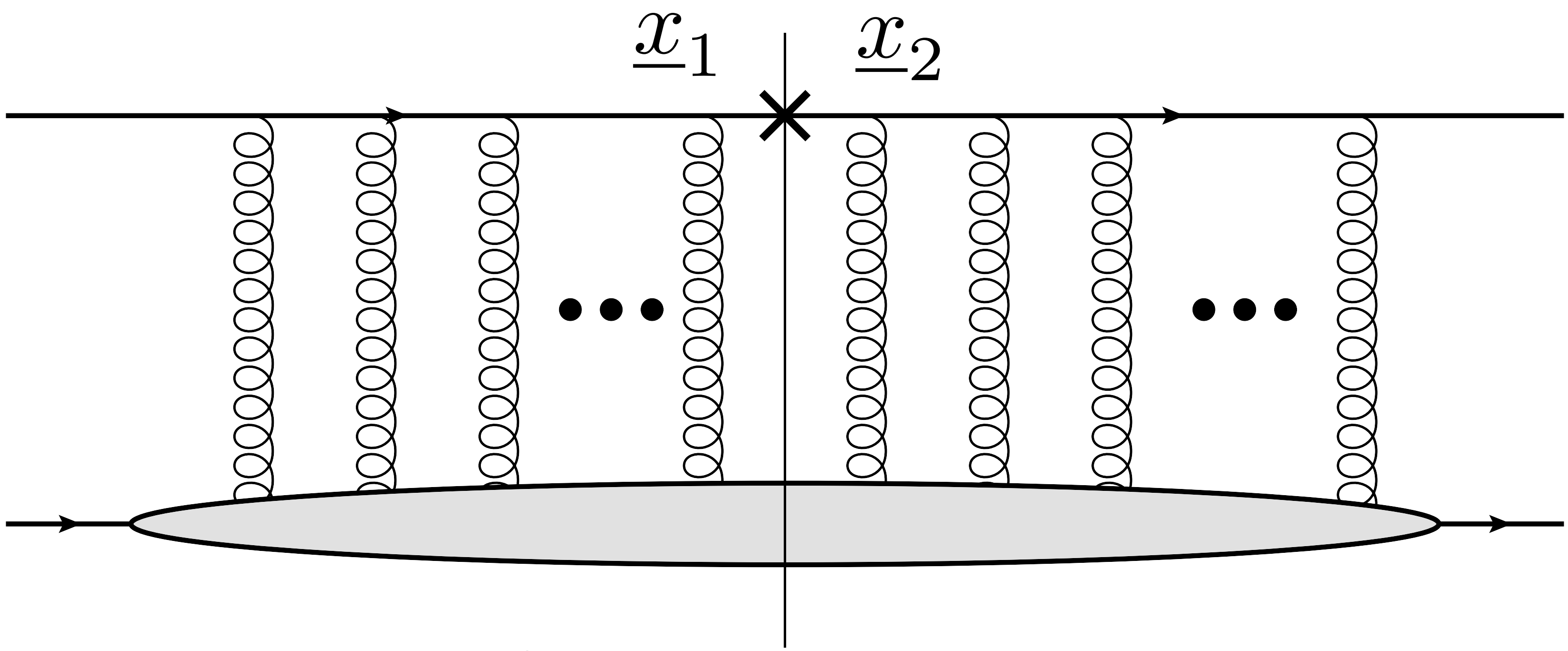
What generates STSA

- To obtain STSA need
  - transverse polarization dependence
    (comes with a factor of “i”)
  - a phase difference by “i” between the amplitude and cc amplitude to cancel the “i” from above (cross section and STSA are real)

(from Qiu and Sterman, early 90’s)

(i) Shooting spin through Color Glass

Forward quark production

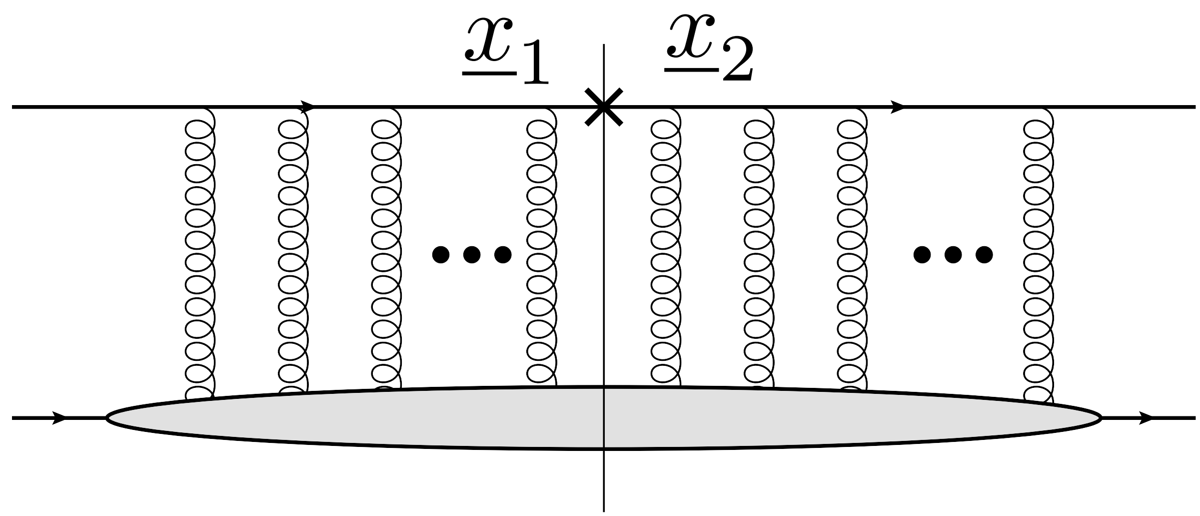


- It is easier to work in transverse coordinate space:

$$\frac{d\sigma}{d^2k\,dy} \propto |M(\underline{k})|^2 = \int d^2x_1\, d^2x_2\, M(\underline{x}_1)\, M(\underline{x}_2)^*\, e^{-i\,\underline{k}\cdot(\underline{x}_1-\underline{x}_2)}$$

- The quark (transverse) coordinates are different on two sides of the cut!

Forward quark production



- The eikonal quark propagator is given by the Wilson line

$$V(\underline{x}) = \mathrm{P}\exp\left[i\, g \int\limits_{-\infty}^{\infty} dx^+\, A^-(x^+, x^- = 0, \underline{x})\right]$$

with the light cone coordinates $\quad x^{\pm} = \dfrac{t \pm z}{\sqrt{2}}$

Forward quark production

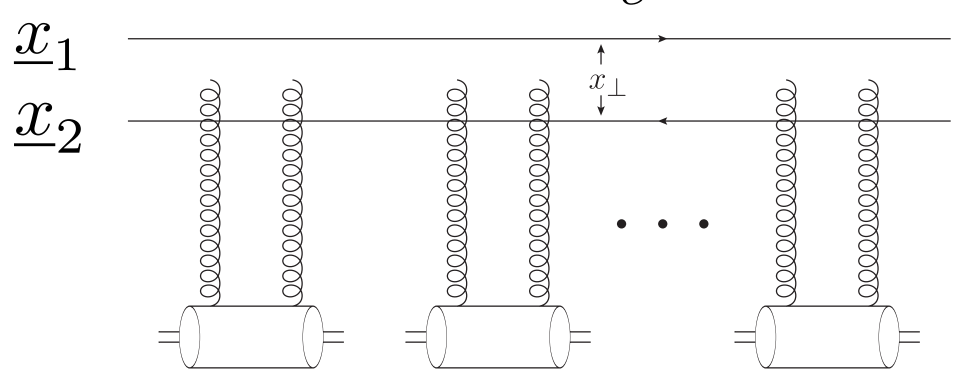
Dumitru, Jalilian '02

- The amplitude squared is

$$\frac{1}{N_c} \left\langle \mathrm{tr} \left\{ [V(\underline{x}_1) - 1] \left[V^\dagger(\underline{x}_2) - 1 \right] \right\} \right\rangle = 1 + \frac{1}{N_c} \left\langle \mathrm{tr} \left[V(\underline{x}_1) \, V^\dagger(\underline{x}_2) \right] \right\rangle$$

- The quark dipole scattering amplitude is

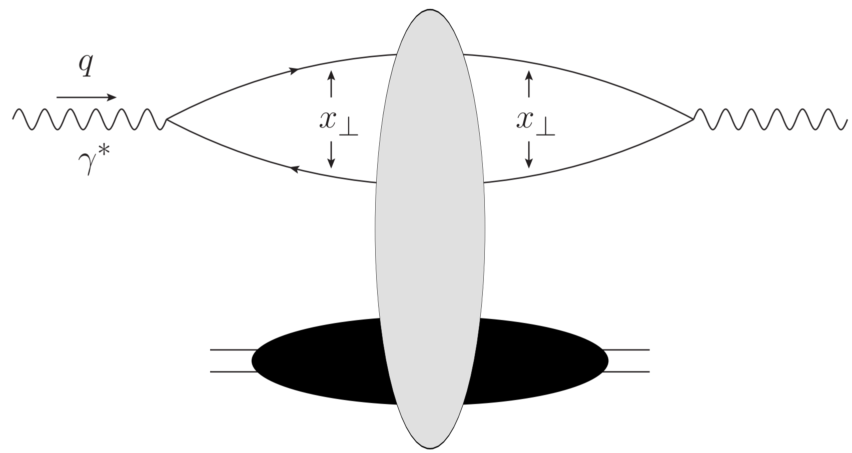
$$N(\underline{x}_1, \underline{x}_2) = 1 - \frac{1}{N_c} \left\langle \mathrm{tr} \left[V(\underline{x}_1) \, V^\dagger(\underline{x}_2) \right] \right\rangle$$



- Hence quark production is related to the dipole amplitude! Valid both in the quasi-classical Glauber-Mueller/McLerran-Venugopalan multiple-rescattering approximation and for the LLA small-x evolution (BFKL/BK/JIMWLK).

Dipole Amplitude

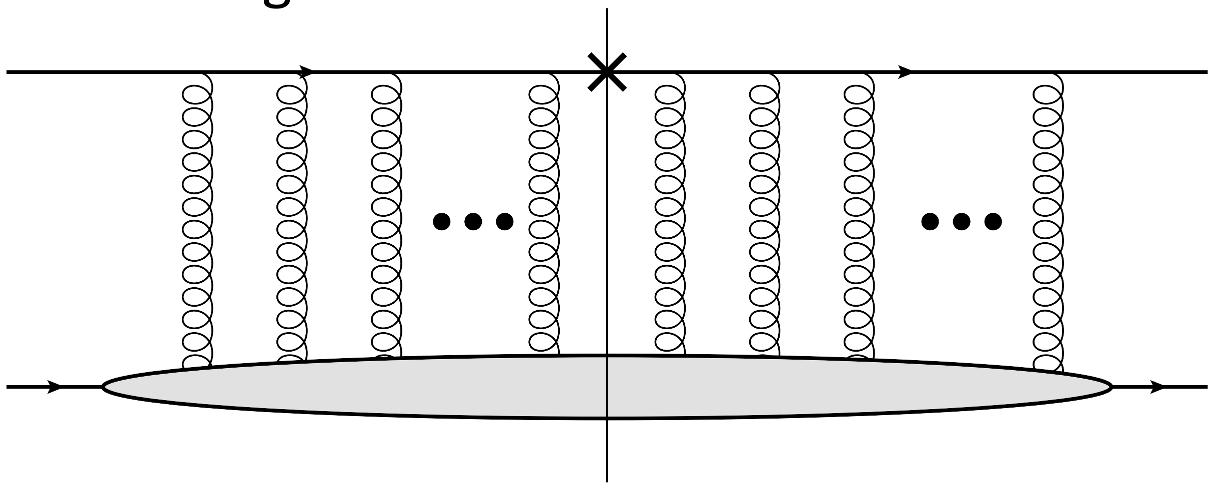
- Dipole scattering amplitude is a universal degree of freedom in CGC.
- It describes the DIS cross section and structure functions:



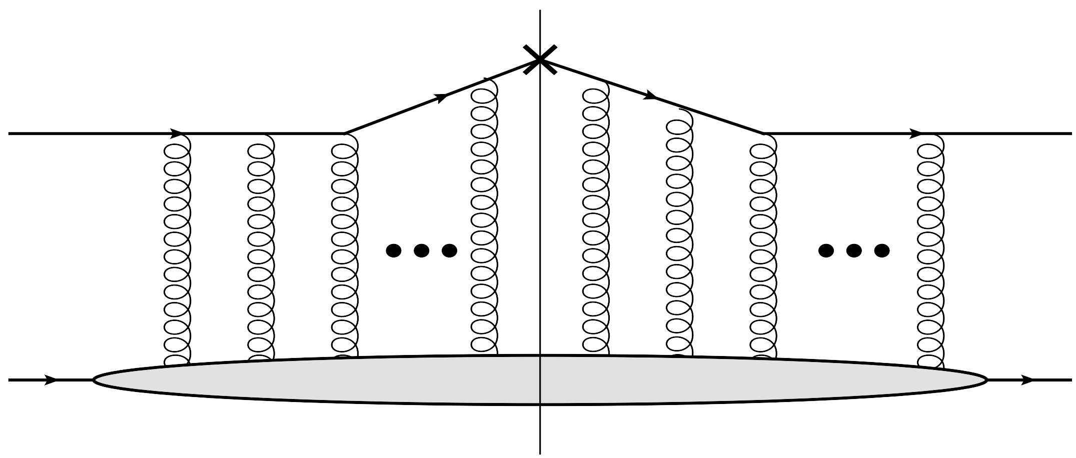
- It also describes single inclusive quark (shown above) and gluon production cross section in DIS and in pA.
- Even works for diffraction in DIS and pA.
- For correlations need also qudrupoles, etc. (J.Jalilian-Marian, Yu.K. '04)

Spin-dependent quark production

- The eikonal quark production is indeed spin-independent, and hence can not generate STSA.

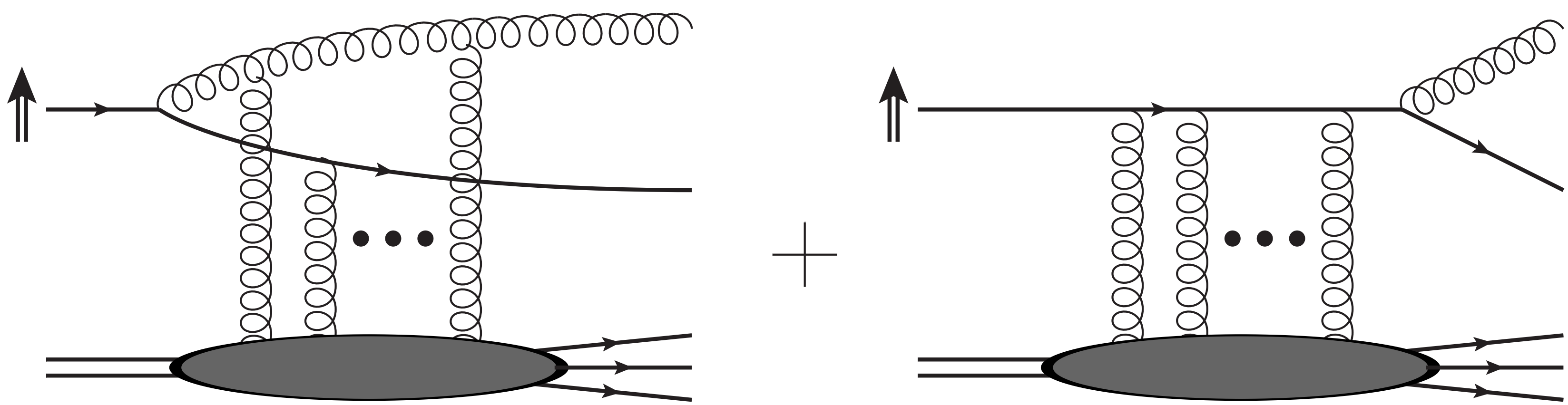


- Simple recoil, while spin-dependent, is suppressed by 1/s:



Spin-dependent quark production

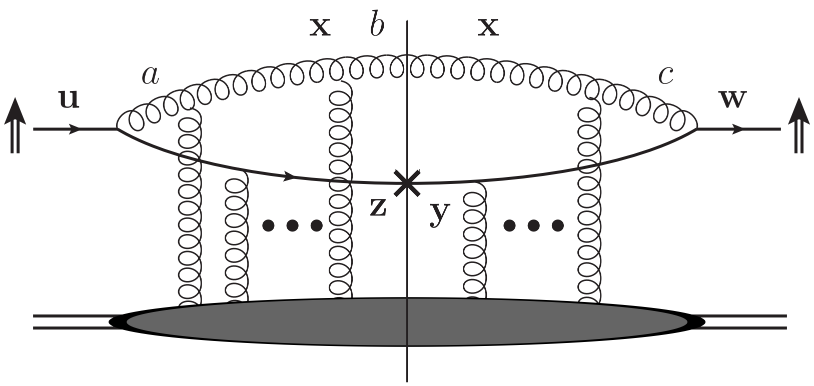
The only way to include spin dependence without 1/s suppression is through the splitting in the projectile before or after the collision with the target:



Let's calculate the corresponding quark production cross section, find its spin-dependent part, and see if it gives an STSA.

Production Cross Section

Squaring the amplitude we get the following diagrams contributing to the production cross section:



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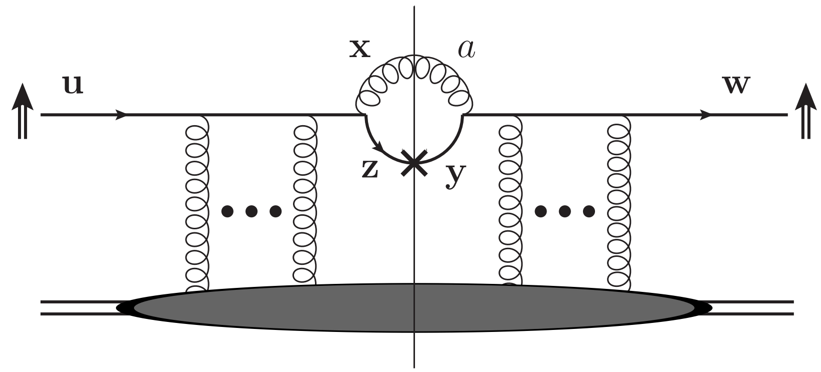

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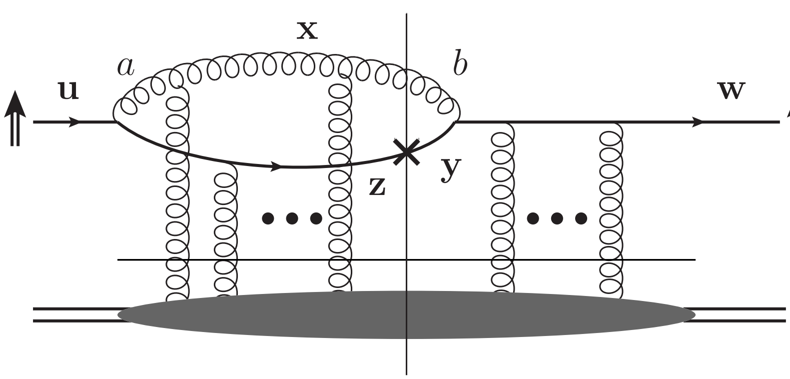


$+$ C. C.

Extracting STSA

- STSA can be thought of as the term proportional to

$$(\vec{S} \times \vec{p}) \cdot \vec{k}$$

- To get a k_T-odd part of the cross section

$$\frac{d\sigma^{(q)}}{d^2k \, dy_q} = \frac{C_F}{2\,(2\pi)^3} \frac{\alpha}{1-\alpha} \int d^2x \, d^2y \, d^2z \, e^{-i\mathbf{k}\cdot(\mathbf{z}-\mathbf{y})} \, \Phi_\chi(\mathbf{z}-\mathbf{x}\,,\,\mathbf{y}-\mathbf{x}) \, \mathcal{I}^{(\mathbf{q})}(\mathbf{x}\,,\,\mathbf{y}\,,\,\mathbf{z})$$

we need the $\mathbf{y} \leftrightarrow \mathbf{z}$ anti-symmetric part of the integrand.

- This may either come from the wave function squared or from the interaction with the target.
- Our LO wave function is symmetric: need to find the anti-symmetric interaction!

C-even and C-odd dipoles

- To find the anti-symmetric interaction we decompose the dipole amplitude into real symmetric (C-even) and imaginary anti-symmetric (C-odd) parts:

$$\frac{1}{N_c} \left\langle \mathrm{tr} \left[V_{\mathbf{x}} \, V_{\mathbf{y}}^{\dagger} \right] \right\rangle = S_{\mathbf{x}\,\mathbf{y}} + i \, O_{\mathbf{x}\,\mathbf{y}}$$

- The symmetric part is

$$S_{\mathbf{x}\,\mathbf{y}} = \frac{1}{2} \left\{ \frac{1}{N_c} \left\langle \mathrm{tr} \left[V_{\mathbf{x}} \, V_{\mathbf{y}}^{\dagger} \right] \right\rangle + \frac{1}{N_c} \left\langle \mathrm{tr} \left[V_{\mathbf{y}} \, V_{\mathbf{x}}^{\dagger} \right] \right\rangle \right\}$$

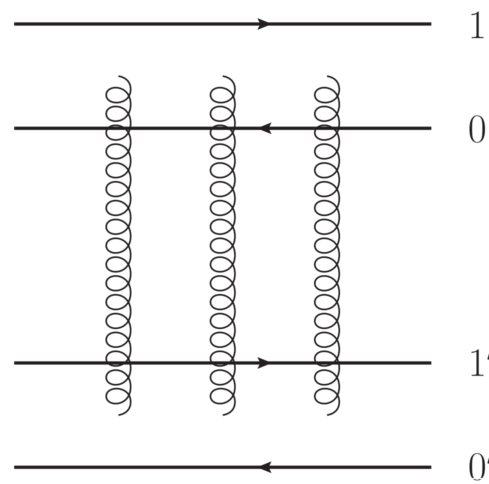
- The anti-symmetric part is

$$O_{\mathbf{x}\,\mathbf{y}} = \frac{1}{2\,i} \left\{ \frac{1}{N_c} \left\langle \mathrm{tr} \left[V_{\mathbf{x}} \, V_{\mathbf{y}}^{\dagger} \right] \right\rangle - \frac{1}{N_c} \left\langle \mathrm{tr} \left[V_{\mathbf{y}} \, V_{\mathbf{x}}^{\dagger} \right] \right\rangle \right\}$$

- As $\mathbf{x} \leftrightarrow \mathbf{y}$ interchanges quark and antiquark, it is C-parity!

C-even and C-odd dipoles

- S_{xy} is the usual C-even dipole amplitude, to be found from the BK/JIMWLK equations: describes DIS, unpolarized quark and gluon production
- O_{xy} is the C-odd odderon exchange amplitude, obeying a different evolution equation (Yu.K., Szymanowski, Wallon '03; Hatta et al '05)
- At LO the odderon is a 3-gluon exchange:



- The intercept of the odderon is zero (Bartels, Lipatov, Vacca '99):

$$\sigma_{odd} \sim s^0 \sim const$$

- In our setup, odderon naturally generates STSA.

STSA in high energy QCD

- When the dust settles, the spin-dependent part of the production cross section is

spin-dependence

$$d(\Delta\sigma^{(q)}) = \frac{C_F}{(2\pi)^3}\,\frac{\alpha}{1-\alpha}\int d^2x\, d^2y\, d^2z\, e^{-i\mathbf{k}\cdot(\mathbf{z}-\mathbf{y})}\,\Phi_{pol}(\mathbf{z}-\mathbf{x}\,,\,\mathbf{y}-\mathbf{x})\,\mathcal{I}^{(\mathbf{q})}_{\mathbf{anti}}(\mathbf{x}\,,\,\mathbf{y}\,,\,\mathbf{z})$$

with the C-odd interaction with the target

phase

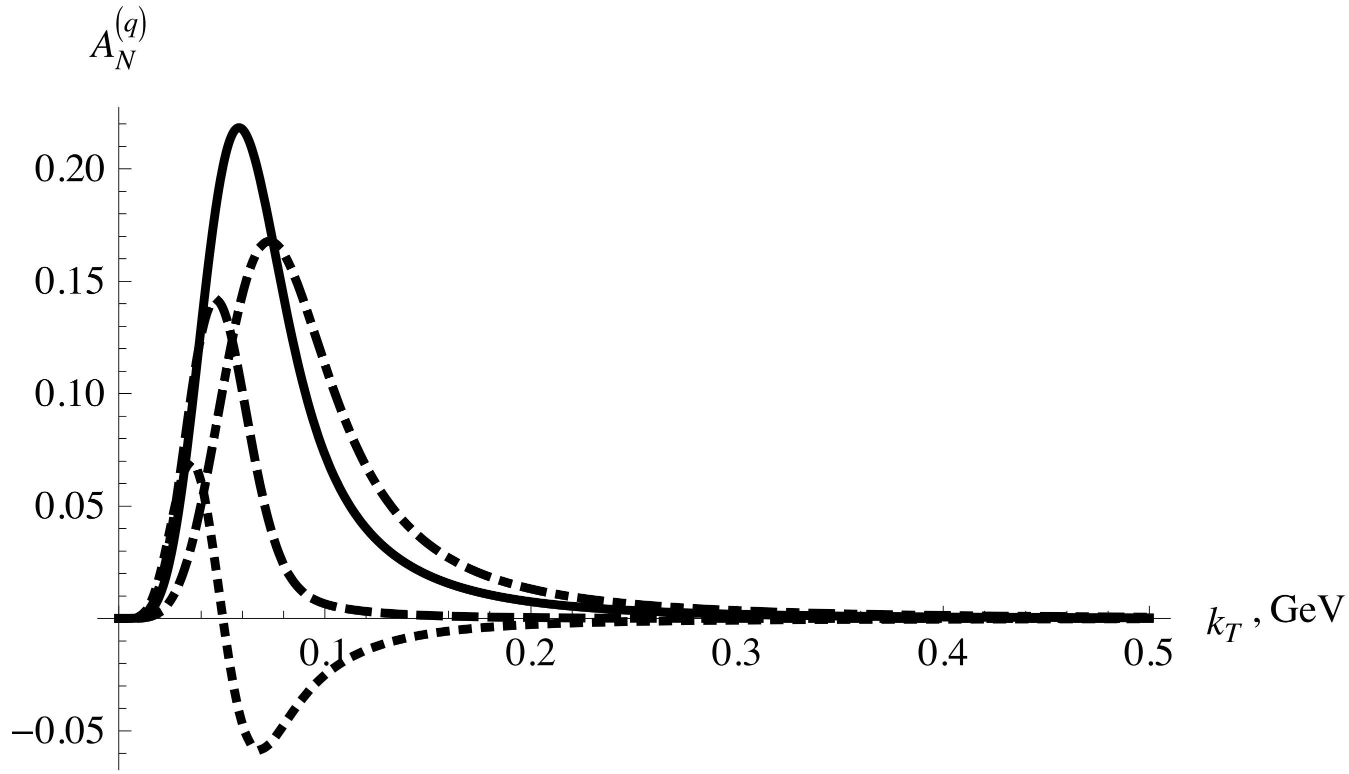
$$\mathcal{I}^{(q)}_{anti}\Big|_{\text{large}-N_c} = i\left[O_{\mathbf{z}\,\mathbf{y}} + O_{\mathbf{u}\,\mathbf{w}} - O_{\mathbf{z}\,\mathbf{x}}\,S_{\mathbf{x}\,\mathbf{w}} - O_{\mathbf{u}\,\mathbf{x}}\,S_{\mathbf{x}\,\mathbf{y}} - S_{\mathbf{z}\,\mathbf{x}}\,O_{\mathbf{x}\,\mathbf{w}} - S_{\mathbf{u}\,\mathbf{x}}\,O_{\mathbf{x}\,\mathbf{y}}\right]$$

- Note that the interaction contains nonlinear terms: only those survive in the end.
- The expression for the interaction at any N_c is known.

Properties of the obtained STSA contribution

Odderon STSA properties

Our odderon STSA is a non-monotonic function of transverse momentum and an increasing function of Feynman-x:



Warning: very crude approximation of the formula. (Q_s=1 GeV)
Curves are for (Feynman-x) α =0.9 (dash-dotted), 0.7 (solid), 0.6 (dashed), 0.5 (dotted).

Dependence on density gradient

- Our STSA is proportional to the square of the gradient of the nuclear profile function T(b):

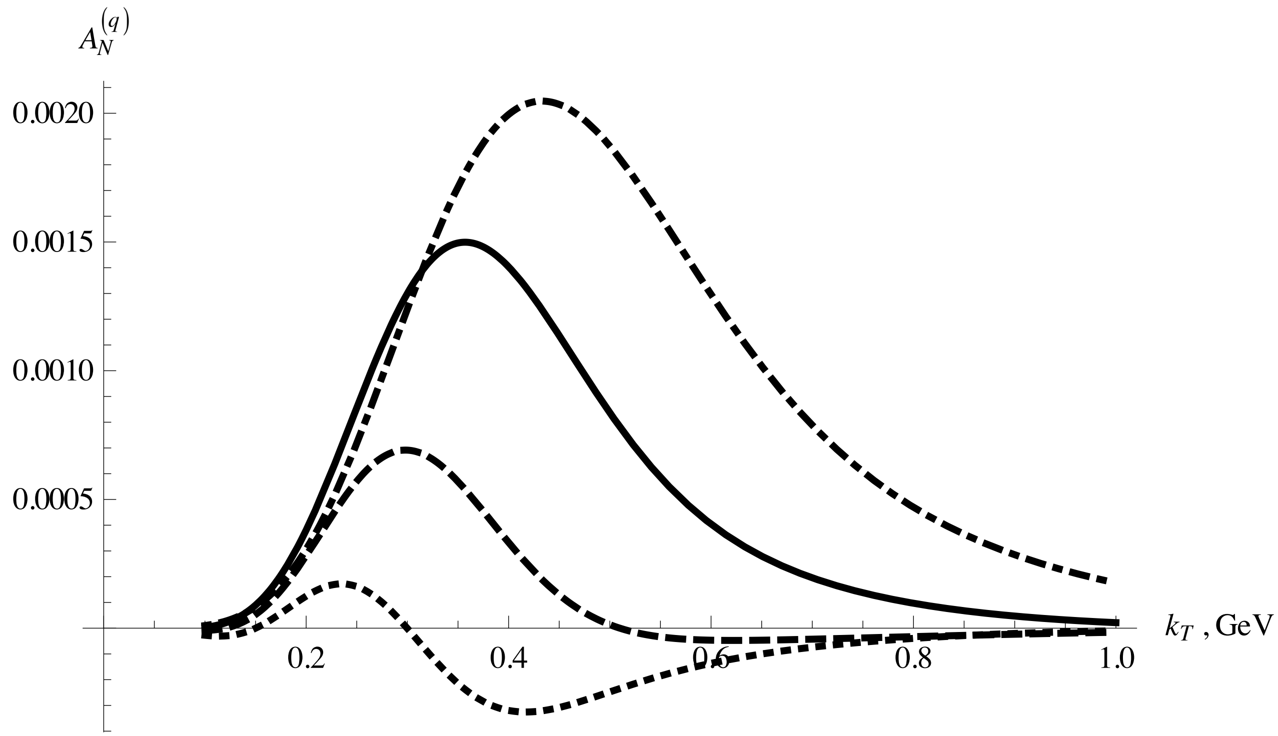
$$A_N \sim \int d^2b \, \left[\nabla \mathbf{T}(\mathbf{b})\right]^2 \ldots$$

- The asymmetry is larger for peripheral collisions, and is dominated by edge effects.

- It is also smaller for nuclei ($p^{\uparrow}$+A) than for the proton target ($p^{\uparrow}$+p).

Odderon STSA properties

To illustrate this we plot A_N with a different large-b (IR) cutoff:



Warning: very crude approximation of the formula. (Q_s=1 GeV)
Curves are for (Feynman-x) α =0.9 (dash-dotted), 0.7 (solid), 0.6 (dashed), 0.5 (dotted).

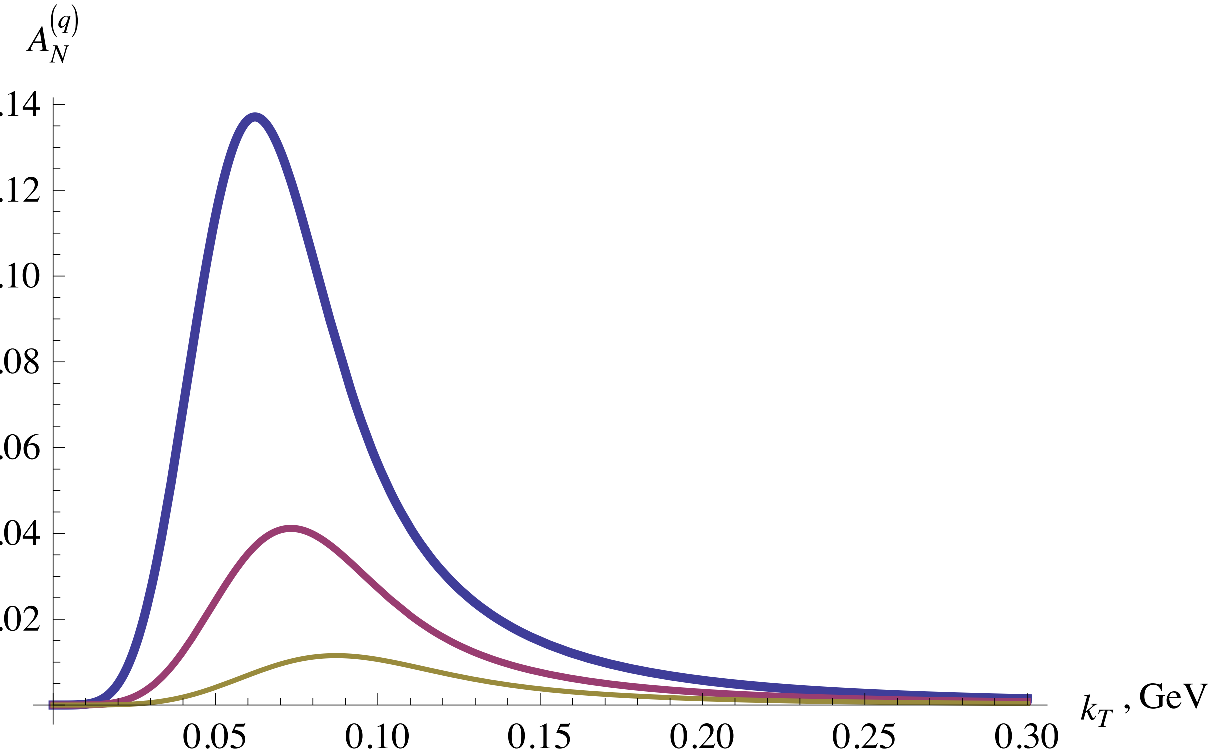
Odderon STSA at high-p_T

- The odderon STSA is a steeply-falling function of p_T:

$$A_N^{(q)}\Big|_{p_T \gg Q_s} \propto \frac{1}{p_T^5}$$

- However, the suppression at high transverse momentum is gone for $p_T \sim Q_s$ (from one to a few GeV).

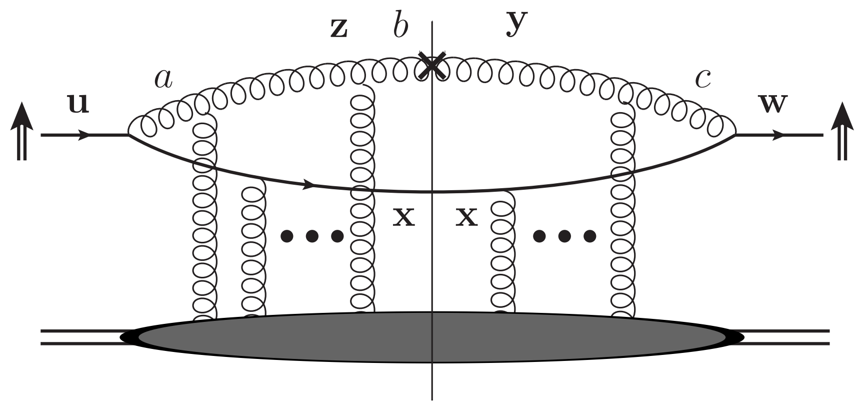
Nuclear (unpolarized) target



Target radius is R=1 fm (top curve), R=1.4 fm (middle curve), R=2 fm (bottom curve): strong suppression of odderon STSA in nuclei. Warning: crude approximation of the exact formula!

Gluon STSA

- is also found along the same lines:



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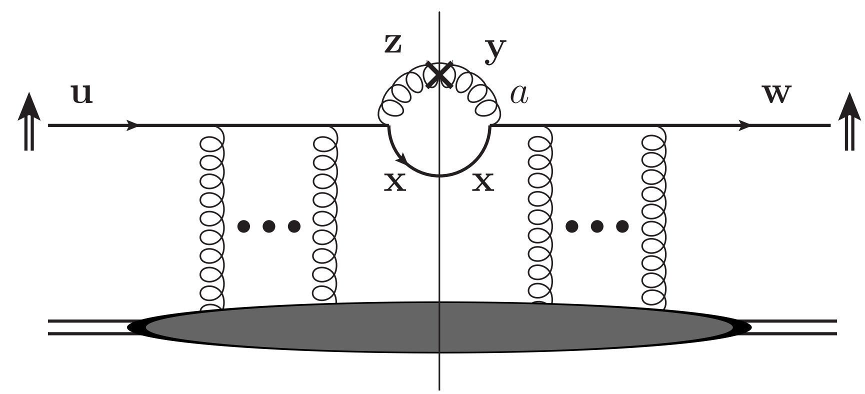

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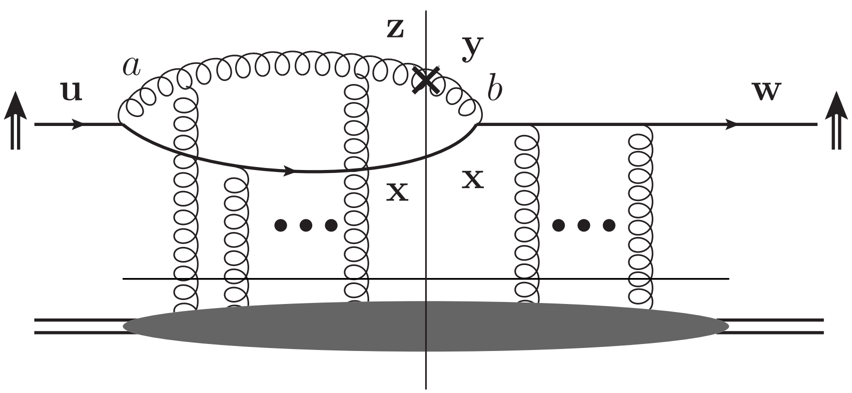


+ c. c.

Properties TBD, likely similar to quark STSA

Prompt photon STSA

- is zero (in this mechanism).
- The photon asymmetry originated in the following spin-dependent production cross-section

$$d(\Delta\sigma^{(\gamma)}) = \frac{1}{(2\pi)^3} \int d^2x\, d^2y\, d^2z\, e^{-i\mathbf{k}\cdot(\mathbf{z}-\mathbf{y})}\, \Phi_{pol}(\mathbf{x}-\mathbf{z}\,,\,\mathbf{x}-\mathbf{y},\alpha)\; \mathcal{I}^{(\gamma)}_{\mathbf{anti}}(\mathbf{x}\,,\,\mathbf{y}\,,\,\mathbf{z})$$

  with the interaction with the target linear in the odderon exchange $\mathcal{I}^{(\gamma)}_{anti} = i\,[O_{\mathbf{u}\,\mathbf{w}} - O_{\mathbf{x}\,\mathbf{w}} - O_{\mathbf{u}\,\mathbf{x}}]$

- This cross section is zero since $\int d^2x\, O_{\mathbf{x},\,\mathbf{x}+\mathbf{y}} = 0$

  for any odd function $O_{\mathbf{x},\,\mathbf{y}} = -O_{\mathbf{y},\,\mathbf{x}}$

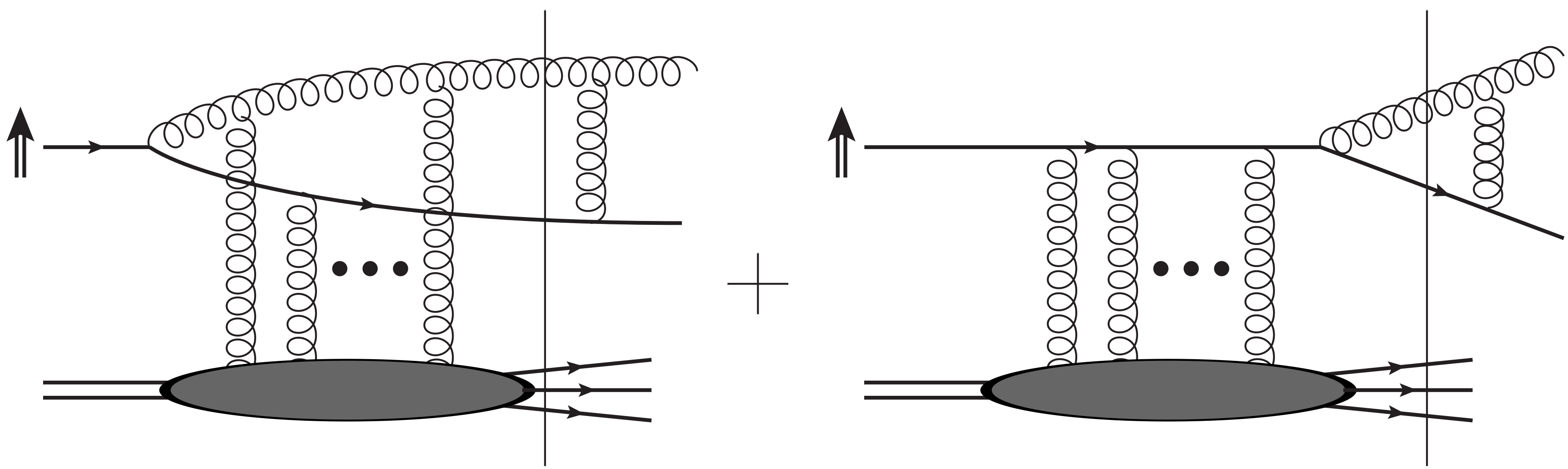
(ii) Sivers effect in Color Glass

Sivers vs Odderon

- In the above STSA mechanism the spin-dependence came from the polarized wave function, while the phase was generated in the interaction. (The wave function was too simple to contain a phase.)
- The phase may also arise in the polarized wave function – this is Sivers effect.
- How does it come into CGC? Is it leading or subleading to the above effect?

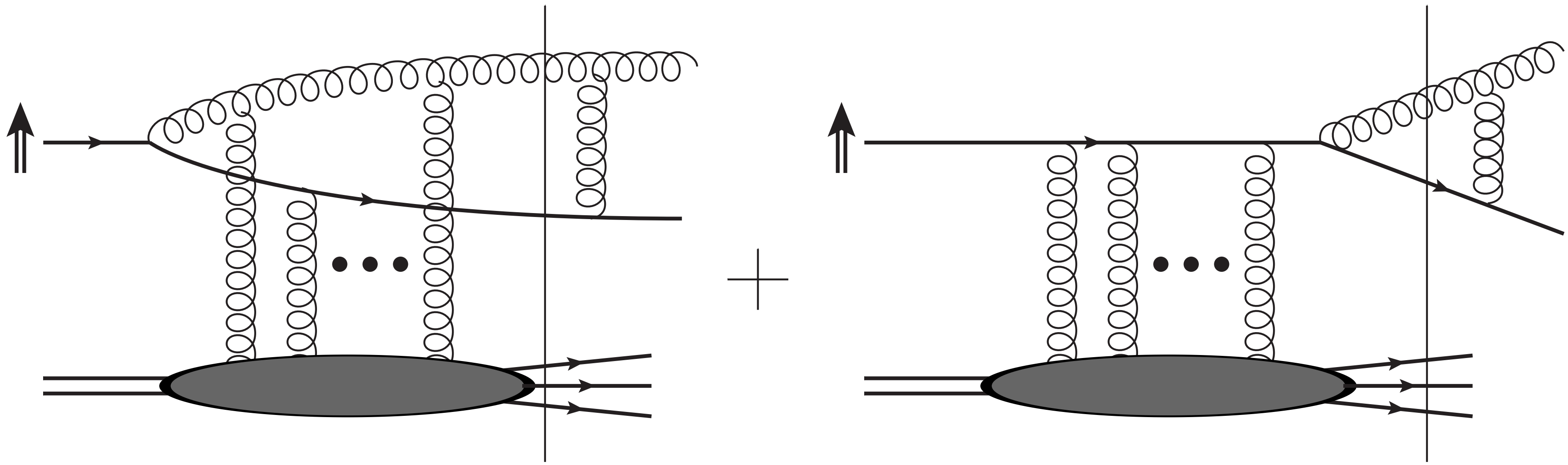
Sivers effect in CGC

- We have explored the case of C-even wave function squared and C-odd interactions.
- One also needs to look into the case of C-odd wave function squared and C-even interaction with the target:



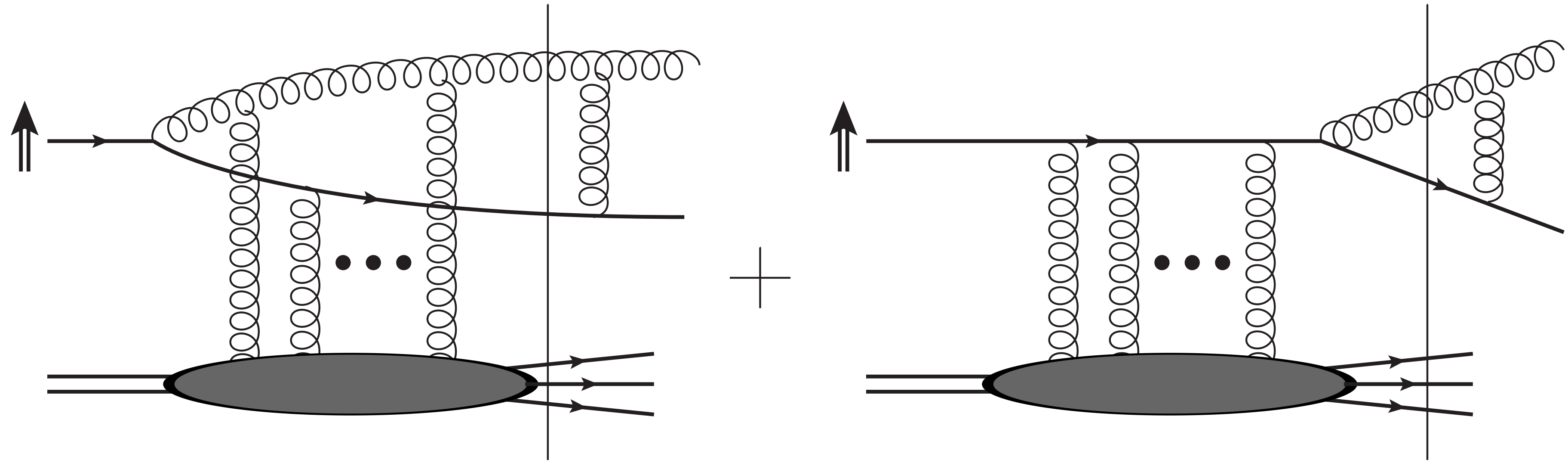
- This is the analogue of the works by Brodsky, Hwang, Schmidt ’02 and Collins ’02 in our saturation language.
- As $O_{xy} \sim \alpha_S \, S_{xy}$ this is of the same order as the odderon STSA.

Sivers effect in CGC



- Both the phase and spin-dependence come from the top of the diagram. The phase is denoted by a cut (Im part = Cutkosky rules).
- However, the extra rescattering generating the phase can only be in the final state as shown (no phase arising in the initial state that we could find).
- Interaction with the target is C-even: no odderons!

Sivers effect in CGC



- This is still work in progress (YK, M. Sievert).
- The answer should look like

phase

$$d\Delta\sigma \propto \int d^2x\, d^2y\, d^2z\, d^2v_1\, d^2v_2\, d\alpha'\, e^{-i\mathbf{k}\cdot(\mathbf{z}-\mathbf{y})}\, i\, A_{2\to 2}(\mathbf{v}_1, \mathbf{v}_2, \mathbf{x}, \mathbf{z})$$

$$\times\, \Phi_{pol}(\mathbf{v}_2 - \mathbf{v}_1, \mathbf{y} - \mathbf{x}; \alpha, \alpha')\, \mathcal{I}_{symm}(\mathbf{x}, \mathbf{y}, \mathbf{v}_2) - (z \leftrightarrow y)$$

spin-dependence

- Very hard to calculate amplitude A in coordinate space (not eikonal, no simplifications, may also need term where spin-dependence is in A).

Sivers effect in CGC

- May be lower-twist than the odderon STSA,

$$A_N \Big|_{p_T \gg Q_s} \propto \frac{1}{p_T^3} \;\; (?\,\mathrm{tbc})$$

  but the two may be comparable for $k_T \sim Q_s$.
- Would lead to non-zero STSA for prompt photons!
- Perhaps the odderon STSA contribution can be found by subtracting photon STSA from the hadron STSA, though there is also the Collins mechanism for hadron STSA.
- Sivers STSA in CGC in p$^{\uparrow}$+A scattering is also likely suppressed compared to p$^{\uparrow}$+p, but more work is needed to check this.

Conclusions

- It seems STSA in p↑+A collisions can be generated by three possible mechanisms: Sivers, Collins, and odderon-mediated.
- Odderon mechanism has right qualitative features of STSA, but falls off fast at high p_T . It is much smaller in p↑+A than in p↑+p. Predicts zero photon/DY STSA.
- Sivers effects is leading at high-p_T (compared to the odderon), and probably is also suppressed in p↑+A vs p↑+p, but this needs to be confirmed. Photon/DY STSA is non-zero.
- I do not have much to say about Collins effect in p↑+A, but fragmentation function may be modified by nuclear environment, possibly modifying the effect.